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# Light Scattering in Donor Lenses

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**Light scattering for normal and cataractous lenses from 21–86 yr old donors was measured *in vitro*. As expected, scattering increased with severity of cataract. Scattering decreased with angle according to a power law. This corresponded to the power law finding for functional straylight measurements in early-cataract patients using white light (power around −2). *In vitro*, straylight increased monotonically from 700 nm (power around −2.3) towards 400 nm (power around −2.0). For extreme cataracts the angular dependence flattened at small angles. The present results suggest that the structures dominating in light scattering differ not by scattering type but by number, and that they are not very small compared to wavelength. The present results were used to specify the separate effects of light absorption and light scattering on lenticular light transmission.**

Lens Cataract Ageing Glare Straylight

Light entering the eye can be scattered by optical imperfections. This scattering can be subdivided into light scattered towards the retina (forward scatter) and light scattered backwards towards the source (backscatter). Forward scatter results in a veiling illuminance superimposed upon the retinal image, causing reduction of retinal contrast. This phenomenon may lead to a variety of complaints, especially glare (review by Vos, 1984). Under pathological conditions, e.g. cataract, scatter can be increased. The corresponding functional impairment is not caused by backscatter as observed with slit-lamp examination.

Recently forward scatter from 3.5 to 25.4 deg scattering angle was studied *in vivo* (de Waard, IJspeert, van den Berg & de Jong, 1992), comparing cataracts and controls. Forward scatter in cataract was found to decrease strongly with scattering angle, approximately according to an inverse square law as with non-cataractous lenses. This was found to be true irrespective of cataract type (nuclear, cortical, subcapsular), which was surprising because of the different morphologies of these cataracts. The present study was undertaken to provide direct evidence for the light-scattering properties of cataract. *In vitro* light-scattering properties of lenses from donor eyes was studied.

Bettelheim and Chylack (1985) also studied scattering in cataracts *in vitro*. They directed their measuring beam on dense areas in the cataractous lenses. They found transmitted intensity to drop from (relative units) 3.77 at 0 deg to 2.89 at 45 deg. Such a flat intensity distribution would correspond to virtually complete loss of imaging properties as in end-stage cataract. Our study aimed at understanding visual function in more early cataracts and with natural pupils. In the study of de Waard *et al.* (1992) all patients had decimal visual acuity between 1.0 and 0.25.

Other attempts to determine optical characteristics of isolated human lenses have concentrated on light transmission (reviews by van Norren & Vos, 1974; Wyszecki & Stiles, 1982). Light transmittance (defined as the fraction of light transmitted) can be derived by integration of the (stray) light distribution over the light collecting aperture. A further incentive to the present study was to understand the dependence of light transmission on light scattering.

## METHODS

In total 16 lenses (see Table 1) were included in the study, ranging from 21 to 86 yr of age (mean 58, SD 23). Eyes with shortest post-mortem enucleation times (mean 8, SD 5 hr) and no history of insult to the lens (e.g. no trauma to the head) were obtained from the cornea bank in Amsterdam. Lenses were carefully isolated and mounted in a special holder, opaque at the sides and with an optically free centre of 8 mm diameter, and placed between, but not in contact with, specially selected cover glasses that were renewed for each lens (van den Berg, 1993). Several immersion media were tried including castor oil (Weale, 1983). As immersion fluid isotonic solutions ($Na^+$ 150, $K^+$ 4, $Ca^{2+}$ 2.2, $Cl^-$ 160 and glucose 6 mmol/l or $Na^+$ 77, $K^+$ 4, $Ca^{2+}$ 2.2, $Cl^-$ 85 and glucose 139 mmol/l, index of refraction 1.336) were used. With these solutions straylight was stable over the duration of the experiment. All lenses were examined with a slitlamp.

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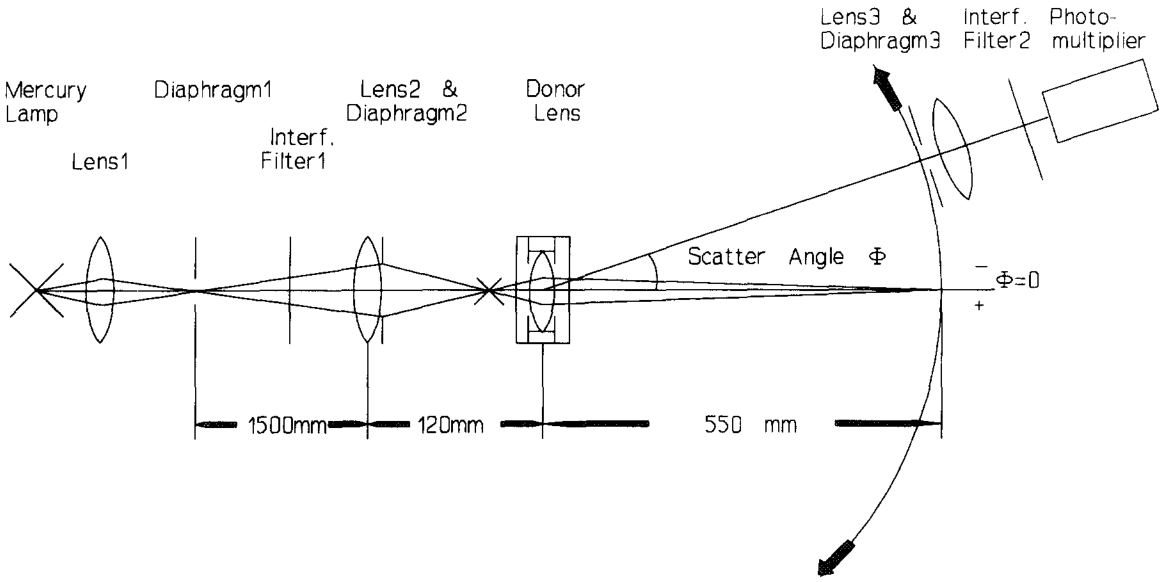


FIGURE 1. Schematic drawing of the setup, not to scale. The combination of lens 3, diaphragm 3, interference filter 2 and photomultiplier could rotate, with the donor lens as centre of rotation. See text for details.

The degree and type of cataract was recorded for the cortex and the nucleus qualitatively by an ophthalmologist (Table 1). Cataractous states varied from completely clear to severe cortical as well as nuclear cataract. Of course post-mortem changes could not be completely excluded. This may invalidate to some extent the results. Measurements were performed over a few hours directly after isolation of the lens. The first run was repeated at the end to check that no change in scattering characteristics took place during the experiment.

Figure 1 is a simplified drawing of the set-up (not to scale). Light from a high pressure mercury lamp was focussed by lens 1 in diaphragm 1. Lens 2 imaged this diaphragm a few centimeters in front of the donor lens (small cross). Interference filter 1 was normally not present (but see below). By shifting lens 2, the distance from focus (small cross) to donor lens was adjusted so that a sharp image (radius about 1 mm) of diaphragm 1 was obtained 550 mm behind the donor lens. A 9 mm radius diaphragm (diaphragm 3) was positioned at this point. The angular size of this diaphragm was 0.93 deg radius (0.00083 sr). *In vivo*, image formation takes place in a medium (vitreous) with a refractive index of 1.336 (Wyszecki & Stiles, 1982). Correction for the difference in index of refraction gives a corresponding radius of 0.7 deg *in vivo*. This is not too far from the 1 deg radius of the test field used in the *in vivo* straylight studies (van den Berg, 1986; van den Berg & Spekreijse, 1987; de Waard *et al.*, 1992). Diaphragm 3 could rotate around the donor lens. With the position of the image defined as 0 deg, diaphragm 3 was rotated from $\Phi = -10$ to $+90$ deg. The divergence of the beam was adjusted by means of diaphragm 2 to a width of 4 mm diameter at the site of the lens. Because the divergence was small (about 3 deg radius), beam diameter did not increase much from anterior to posterior surface of the donor lens. Lens 3 imaged the donor lens on the photomultiplier. The image (diameter about 2 mm) of the illuminated part of the donor lens was centred upon the 9 mm diameter sensitive area of the photomultiplier. In this way, all light collected by diaphragm 3 was fed into the photomultiplier. Directly in front of the photomultiplier an interference filter (interference filter 2 in Fig. 1, half bandwidth 10 nm) was located. For most lenses scans were made with interference filter 2 of 400, 500, 602 and 700 nm. If the intensity was too high for the photomultiplier, neutral density filters were inserted directly in front of interference filter 2, calibrated for each interference filter used. The photomultiplier was used as a photon counter, giving $I_1(\Phi)$ in counts/sec. Corrections were made for dark count, dead time and neutral density filter, giving $I_2(\Phi)$ in counts/sec. The intensity of scattered light per steradian was calculated as

$$I_3(\Phi) = I_2(\Phi)/0.00083.$$

$I_3(\Phi)$ was numerically integrated over the solid angle from $\Phi = 0$ to 90 deg to derive the total amount of counts/sec transmitted by the lens in the forward half space

$$I_{tr} = \pi/180 \int I_3(\Phi) 2\pi \sin(\Phi) d\Phi.$$

For calibration, after each experiment the lens was removed from the holder and the measurement was repeated for each interference filter used, but with diaphragm 3 at 0.645 mm radius (0.0000043 sr). Note that in the absence of the donor lens, no imaging of the focus (small cross) took place, and the beam diverged. These control measurements ($C_1(\Phi)$]) were treated identically as the measurements with donor lens

$$C_3(\Phi) = C_2(\Phi)/0.0000043.$$

The integration yielded calibration value

$$C_{tr} = \pi/180 \int C_3(\Phi) 2\pi \sin(\Phi) d\Phi.$$

$T = I_{tr}/C_{tr}$ gives the transmittance value for the donor lens. True transmittance values were underestimated because $T$ does not apply to the full forward half space, but to a cone with a half top-angle of about 48 deg. According to Snell's law, the sequence immersion fluid–glass–air has the same limit angle as the sequence immersion fluid–air, which is about 48 deg. Some indication of the error in $T$ can be obtained by estimating the amount of light scattered by a donor lens between say 45 and 90 deg. For this purpose, the power law found in this paper was extrapolated to 90 deg. On this basis it can be calculated that for the best lens about 0.5% and for the worst lens about 5% was scattered between 45 and 90 deg. In fact the error is larger, because some of the light scattered at angles smaller than 45 deg was intercepted in the holder, or more strongly back-reflected at the posterior immersion fluid–glass–air interface as compared to light at 0 deg. In total these losses were calculated to be maximally the same (0.5–5%). $T$ was not corrected for these losses. The calibration measurements also yielded a check on potential scattering by the holder and immersion fluid (except for the central 3 deg radius). Note that in the normal lens, straylight has a rather low intensity, so that slight amounts of dirt or dust might influence the measurements. For all lenses, angles and wavelengths, the intensity of this scattering was (much) less than 10% of the scattering by the lens.

As a check on the angular dependence of the scattering measurements, samples with known angular characteristics were measured. These samples were the autofluorescence of the lens itself as well as a suspension of monodisperse polystyrene latex spheres of 60 nm diameter (Polysciences Inc.). An excitation interference filter (400 or 420 nm) could be inserted in front of the donor lens for autofluorescence measurements (interference filter 1 in Fig. 1). For analysis a filter of 520 nm was used (interference filter 2 in Fig. 1). Since autofluorescence is basically isotropic, the autofluorescence scans should be flat compared to single-wavelength scans. Indeed, for small angles the autofluorescence scans were perfectly flat [see van den Berg (1993) for actual curves]. But at 50 deg the measured intensity had dropped by about 0.2 log units, because of refraction and reflection at the immersion fluid–glass–air interface in combination with screening effects in the holder. Note that the volume from which light was detected was effectively a cylinder of 4 mm diameter reaching from anterior side to posterior side of the donor lens. At large angles the cylinder was partly vignetted because the 8 mm diameter opening at the posterior side was located at about 3.5 mm distance from the anterior side. At right angles (90 deg) the holder obstructed all light. The deviation in the autofluorescence scans (0.0 log units for small angles to 0.2 log units at 50 deg) were used as correction for $I_2(\Phi)$, giving $I_4(\Phi)$. For latex spheres, measured scattering characteristics proved to follow known theory (van de Hulst, 1981).

$I_4(\Phi)$ was divided by $I_{tr}$ to obtain the normalized light-scattering characteristics of Figs 2–5 where log $I_4(\Phi)/I_{tr}$ is plotted. $T = I_{tr}/C_{tr}$ was used as large aperture transmittance value. Log $T_{wavelength}/T_{700}$ nm is plotted in Fig. 6. The intensity measured at 0 deg (with the 0.7 deg radius diaphragm) $I_4(0)$ was divided by $I_{tr}$ to derive the extra transmission loss for small apertures. Log $T_{0.7}$/T with $T_{0.7} = I_4(0)/C_{tr}$ is plotted in Fig. 7 as function of wavelength. In physical light-scattering theory often the Rayleigh ratio is used, defined as scattered power per unit solid angle normalized both by input irradiance and by scattering volume (see e.g. van de Hulst, 1981). With correction for absorption effects, and since the irradiated part of the sample has the same surface as the measured part, the Rayleigh ratio in our case would approximately equal $I_4(\Phi)/(I_{tr} \times d \times 0.00083)$, with $d$ the length of the 4 mm diameter central cylindrical part of the lens. But the Rayleigh ratio is usually applied to homogeneous samples, whereas we studied the scattering of the lens as a whole, a complex structure. Throughout this paper Briggsian (base 10) logarithms are used.

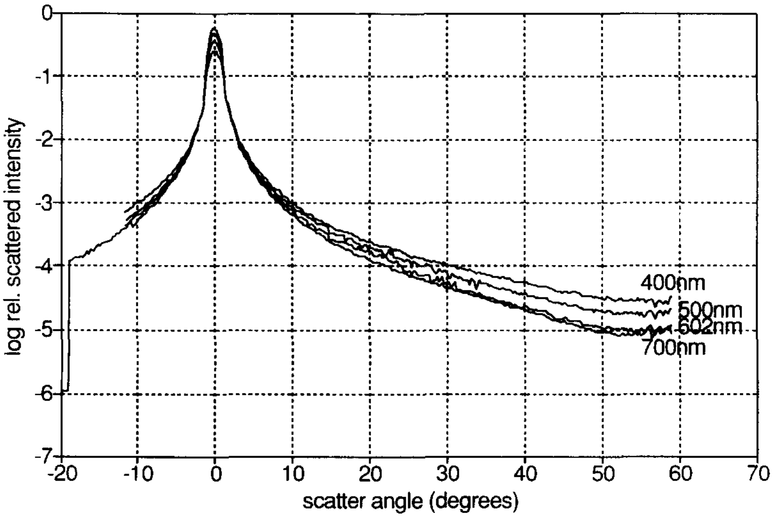


FIGURE 2. Normalized light scattering characteristics for an 81 yr old cataractous lens (ID# 255). The shape of the peak (a few degrees around zero) has no meaning because it is determined by the size of the measuring diaphragm. Plotted is log $I_4(\Phi)/I_{tr}$. See text for details.

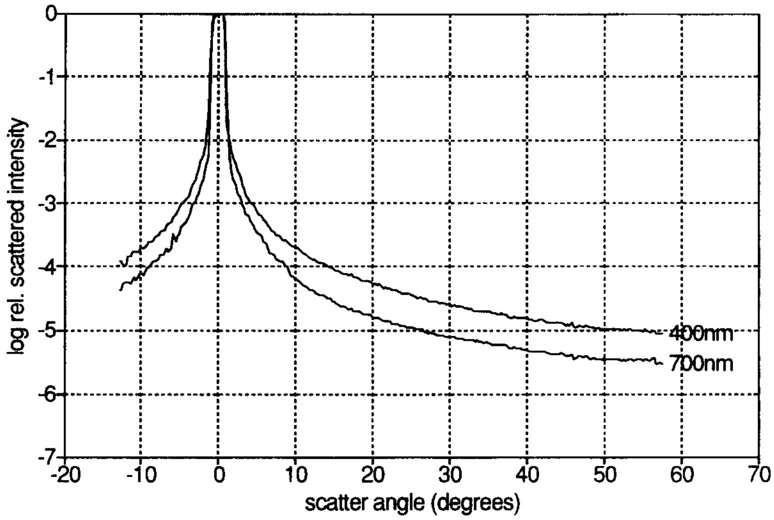


FIGURE 3. Same as Fig. 2, but for a 24 yr old clear lens (ID# 651).

## RESULTS

Figure 2 gives the scattering characteristics [log $I_4(\Phi)/I_{tr}$] for a cataractous lens (ID# 255) and Fig. 3 for the clearest lens in our sample (ID# 651, only two wavelengths measured). Note that the width of the peaks has no meaning. The half-width corresponds approximately to 2 times the diameter of the measuring diaphragm. As might be expected, in all lenses scattered light intensity was approximately symmetric from $-10$ to $+10$ deg. Figures 4 and 5 present the positive parts of Figs 2 and 3 in log–log plots to illustrate a power law behaviour:

$$I_4(\Phi)/I_{tr}) = 10^{\text{const.}} \times \Phi^p$$

so that

$$\log(I_4(\Phi)/I_{tr}) = const. + p \times \log(\Phi)$$

where $p$ is the regression slope in the log–log plots. By linear regression of the log–log plots from 2 to 50 deg (1.5–35 deg internally), $p$ and the constant were estimated. The log–log characteristics of two lenses (ID# 167 and 176) deviated more then 0.3 log units from the fitted regression line. Their shapes were not linear but convex, especially for 400 nm. This was considered to invalidate the regression analysis of these lenses. For all other lenses the deviation was $<0.3$ log unit.

Table 1 lists some key parameters for each of the 16 lenses. Some values are missing (—) because for lens 315 at 400 nm an artefact occurred, and for lens 724 the complete 400 nm measurement was missing. Column 5 shows that for 400 nm the lenticular transmittance for large reception aperture (45 deg), log($T$) ran between $-0.78$ and $-3.35$. Column 6 shows that the extra transmission loss when the reception aperture is smaller (0.7 deg), $\log(T_{0.7^\circ}/T)$ can be considerable, up to $-0.88$. Column 7 shows that this is much less for 700 nm.

Columns 8–11 give the parameters (the power $p$ and the constant) of the scattering characteristics in the log–log plots, estimated from linear regression analysis. In columns 10 and 11 it can be seen that the intensity of scattered light (the constant) is higher for more cataractous lenses. Within each lens the constant was

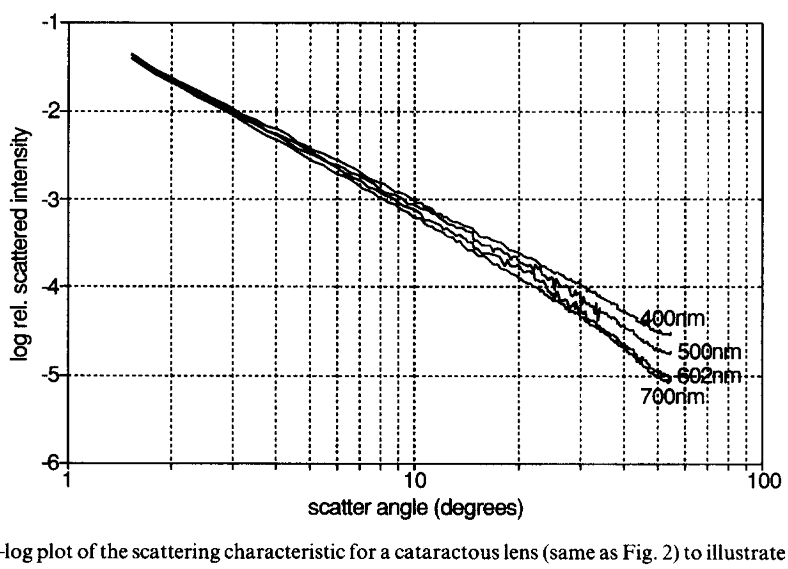


FIGURE 4. Log–log plot of the scattering characteristic for a cataractous lens (same as Fig. 2) to illustrate power law dependence.

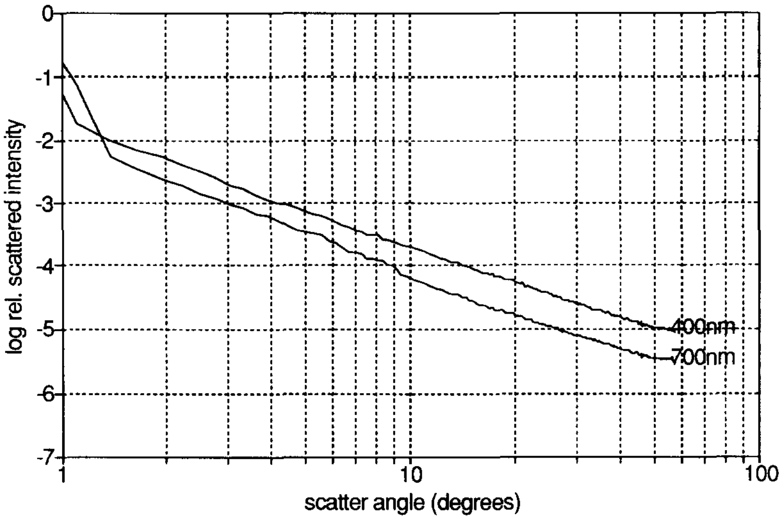


FIGURE 5. Log–log plot of the scattering characteristic for a clear lens (same as Fig. 3) to illustrate power law dependence.

almost the same for the different wavelengths. Because of differences in $p$, 400 nm had the highest curve ($p$ closest to $-2.0$) and 700 nm the lowest ($p$ closest to $-2.3$) in all lenses. In order to judge the wavelength dependent differences within the lenses more closely, in Table 2 mean values for the parameters themselves, as well as for their differences with the lens average values, are given with the standard deviations. In these mean values lenses 167 and 176 were excluded because the power law approximation seemed to be invalid, and lenses 290, 315, 651 and 724 were excluded because regression results were not available for all four wavelengths.

To judge the relative position of the curves for the different wavelengths more directly, the 10 deg values (the mid point in the log–log plots) for the regression lines were calculated and, as above, the differences from the mean values were determined for the same group of lenses (Table 2). Note that the differences in scattered intensity are larger for angles $> 10$ deg and smaller for angles $< 10$ deg. Without the use of statistical calculation it is clear from these figures that the differences between the wavelengths were rather constant (SD approx. 0.05 log units). At 10 deg, scattering is 0.34 log units (a factor of 2.2) more intense for 400 nm as compared to 700 nm. The differences between the lenses was not so much in the *shape* of the bundle of four scattering characteristics, but in the *position*, i.e. the constant in the regression equation.

In Fig. 6 transmittance values (large aperture) relative to the value for 700 nm are shown for four age groups as derived from the scattering characteristics (see Methods). From high to low the curves give mean log $T_{\text{wavelength}}/T_{700\text{ nm}}$ for 20–40, 40–60, 60–80 and 80+ yr of age (means $\pm$ SD: $24 \pm 3$, $48 \pm 5$, $70 \pm 3$ and $83 \pm 3$ yr respectively). Note that these average curves are based on small numbers of

TABLE 1. Key parameters for the 16 donor lenses

| ID No. | Age (yr) | Enucleation (hr) | Cataract | Transmittance values* Log $T$ 400 nm | Log $(T_{0.7}/T)$ 400 nm | Log $(T_{0.7}/T)$ 700 nm | Regression parameters† −Power 400 nm | −Power 700 nm | Log (−const.) 400 nm | Log (−const.) 700 nm |
|---|---|---|---|---|---|---|---|---|---|---|
| 167 | 86 | 9 | Severe nuclear | −3.35 | −0.46 | −0.07 | 1.66 | 2.22 | 1.15 | 0.78 |
| 176 | 68 | 6 | Severe nucl. + cort. | −2.53 | −0.88 | −0.42 | 1.77 | 2.41 | 1.00 | 0.70 |
| 189 | 44 | 15 | Slight cortical | −1.61 | −0.48 | −0.26 | 2.15 | 2.33 | 1.34 | 1.49 |
| 219 | 70 | 14 | Severe nuclear | −1.80 | −0.71 | −0.37 | 2.28 | 2.52 | 0.74 | 0.77 |
| 230 | 21 | 12 | Clear | −0.78 | −0.43 | −0.18 | 1.99 | 2.03 | 1.23 | 1.57 |
| 235 | 69 | 7 | Slight nuclear | −2.29 | −0.31 | −0.05 | 1.90 | 2.15 | 1.20 | 1.35 |
| 255 | 81 | 7 | Severe cort. + nucl. | −1.84 | −0.58 | −0.22 | 1.99 | 2.22 | 0.98 | 0.98 |
| 263 | 28 | 8 | Clear | −1.46 | −0.33 | −0.21 | 2.18 | 2.41 | 1.13 | 1.20 |
| 290 | 69 | 1 | Slight nuclear | −2.73 | −0.30 | −0.15 | 1.98 | 2.22 | 1.32 | 1.51 |
| 296 | 22 | 7 | Assessment missing | −1.42 | −0.59 | −0.30 | 2.15 | 2.26 | 0.90 | 0.98 |
| 315 | 81 | 0 | Severe cort. + nucl. | −2.40 | −0.18 | −0.11 | — | 2.48 | — | 0.98 |
| 391 | 76 | 2 | Severe cort. + nucl. | −1.70 | −0.37 | −0.21 | 1.92 | 2.22 | 0.90 | 1.05 |
| 651 | 24 | 14 | Clear | −1.37 | 0.02 | 0.01 | 1.92 | 2.11 | 1.73 | 1.96 |
| 670 | 51 | 13 | Clear | −1.61 | −0.24 | −0.15 | 1.99 | 2.33 | 1.20 | 1.28 |
| 703 | 73 | 2 | Moderate cort. + nucl. | −2.94 | −0.50 | −0.12 | 2.20 | 2.60 | 0.83 | 0.83 |
| 724 | 72 | 11 | Moderate nuclear | — | — | −0.23 | — | 2.63 | — | 0.87 |

* $T$, transmittance at the specified wavelength (400 nm) for large receptance angle (45 deg). $T_{0.7}$, transmittance at the specified wavelength (400 or 700 nm) for small receptance angle (0.7 deg).

† Parameters for the light scattering characteristics were estimated by linear regression fitting on log–log scales: $\log(I_4(\Phi)/I_{tr})$ = constant + power × log(scatter angle $\Phi$ in deg).

TABLE 2. Mean regression data (and SDs)

| Wavelength | 400 nm | 500 nm | 602 nm | 700 nm |
|---|---|---|---|---|
| Power $p$ | −2.08 (0.13) | −2.14 (0.15) | −2.2 (0.17)6 | −2.31 (0.17) |
| Constant | −1.05 (0.20) | −1.10 (0.25) | −1.12 (0.26) | −1.15 (0.27) |
| *Within lens effects* | | | | |
| $p$ − (lens average $p$) | 0.12 (0.06) | 0.05 (0.05) | −0.06 (0.04) | −0.11 (0.05) |
| Constant − (lens average constant) | 0.06 (0.05) | 0.00 (0.03) | 0.02 (0.02) | −0.05 (0.05) |
| 10 deg value − (lens average 10 deg value) | 0.18 (0.04) | 0.06 (0.05) | −0.08 (0.03) | −0.16 (0.05) |

lenses. Log $T_{700\,nm}$ had a mean of −0.09 (81%) over all lenses.

For the small (0.7 deg radius) aperture, transmittance values were of course smaller. The difference between small and large aperture transmittance are listed as log $T_{0.7}/T$ in Table 1, columns 6 and 7 for 400 and 700 nm respectively. The difference increased with the (cataractous) state of the lens. Figure 7 shows the same data as function of wavelength. For the clearest lens (ID# 651; uppermost curve) the difference was virtually zero (about 0.01 log unit). For the most cataractous lens (ID# 176; lowermost curve in Fig. 7) the differences were: 0.88, 0.61, 0.51 and 0.42 log units for 400, 500, 602 and 700 nm respectively. Figure 7 shows that for all lenses these curves were approximately linear with wavelength. The difference was always largest for 400 nm in correspondence with the above mentioned fact that scattered intensity was always strongest for 400 nm.

## DISCUSSION

It must be noted that the approximation of the scattering characteristics with a power law is chosen for data reduction. No physical model is proposed. The precision of this approximation was however not always the same. The curves deviated up to 0.3 log unit from the fitted regression line. For two lenses the deviation was >0.3 log units. See below for an interpretation of this finding.

The analysis presented is partly based on the assumption that scattering shows rotational symmetry. The angular distribution was measured in only one plane, and this was assumed to represent the angular distribution in all planes. Note that the fibre structure of normal lenses is more or less rotationally symmetrical and that the use of natural (unpolarized) light favours rotational symmetry. Indeed, in all cases the angular distribution was more or less symmetrical around 0 deg (point symmetry). Note that the orientation of the lenses was random with respect to the plane of measurement (but always the same with respect to the direction of the beam). But, especially in more cataractous lenses, deviations from point symmetry were also seen. Our disregard of potential rotational asymmetries may have induced some variance in the data.

The angular dependence of scattered light, was characterized with the power $p$, and was found to be about the same for most lenses, including those with manifest cataracts (Table 1). This is unexpected because the different types of cataract have different morphologies. But an *in vivo* study on functional light scattering in cataractous eyes (de Waard *et al.*, 1992), has suggested the same.

de Waard *et al.* (1992) estimated scattering for the isolated cataract. It proved to follow the classical power

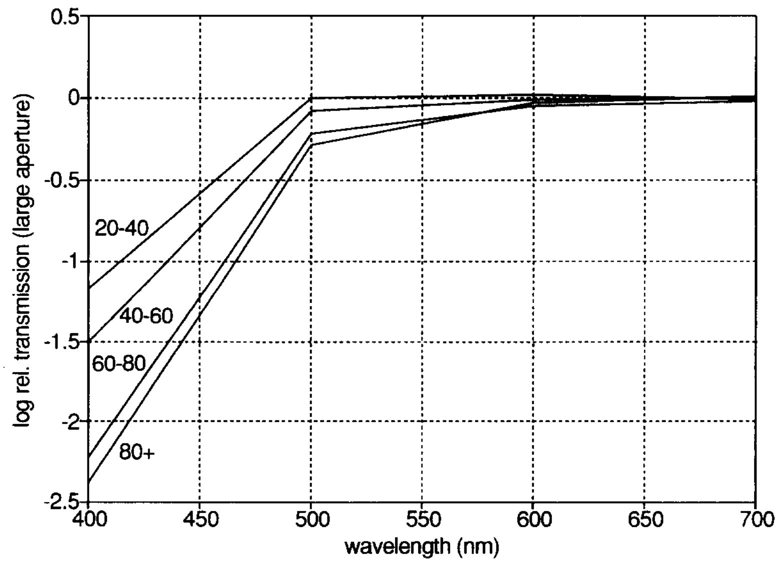


FIGURE 6. Lens transmission derived from light scattering characteristics for a large aperture (45 deg radius), relative to the 700 nm value. Mean values of log $T_{wavelength}/T_{700\,nm}$ for age groups are plotted. From top to bottom the mean ages are 24, 48, 70 and 83 yr. See text for details.

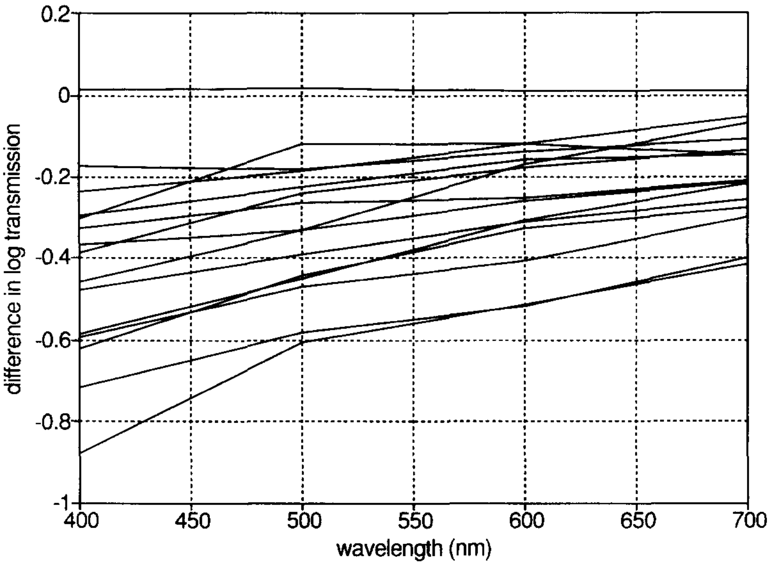


FIGURE 7. Difference in lens transmission for a small aperture (0.7 deg radius) as compared to a large aperture. Plotted is log $I_4(0)/I_{tr}$. Lens 724 is not included since the 400 nm measurement misses. See text for details.

law for normal eyes (Vos, 1984). The powers for all the cataract subpopulations were found to be between −2.0 (Stiles-Holladay see Vos, 1984) and −2.3 (de Waard *et al.*, 1992). As mentioned in the Introduction, this result seemed to contradict the *in vitro* data of Bettelheim and Chylack (1985). But, contrary to our study, theirs was not intended to reflect the effects of cataract on visual function and their approach was essentially different from ours. It seems remarkable that the present *in vitro* data show such close correspondence to the *in vivo* data.

As a practical consequence of the finding that the angular dependence does not differ (much) between cataracts it was mentioned (de Waard *et al.*, 1992) that straylight measurement for only one angle suffices: from one straylight value the complete straylight function more or less follows. This conclusion is now strengthened since the angular dependence was found to be the same between different cataracts over a larger angular domain (1.5–35 deg internally).

The results document the different effects caused by light absorption and light scattering on light transmission through the human lens. Light absorption is most closely estimated with the large aperture transmittance $T = I_{tr}/C_{tr}$. Light scattering is only properly estimated if the transmitted scattered intensity is corrected for absorption effects. This is achieved by division of $I_4(\Phi)$ with the large aperture transmitted intensity: $I_4(\Phi)/I_{tr}$. The constant of the regression line fitted to this function gives the intensity of scattering. Figure 7 shows that light scattering can influence transmittance data (for reviews see van Norren & Vos, 1974; Wyszecki & Stiles, 1982) considerably if methods are used with small (effective) apertures (van Norren & Vos, 1974). Such is especially the case with psychophysical and *in vivo* optical methods. Because of this, the literature (Wyszecki & Stiles, 1982) value of 0.16 for lens optical density at long wavelengths, might well be too high. Note that even the present estimate of 0.09 is probably too high. It must be regarded as an upper limit because it represents less then optimal conditions (post mortem, *in vitro* and partly cataractous).

It has long been established (reviews by van Norren & Vos, 1974; Wyszecki & Stiles, 1982) that the yellowing of the lens with age corresponds with a wavelength dependence of lens absorption. This was also found by the present approach (Fig. 6). It now appears that light scattering in the lens is also wavelength dependent. The shape of this wavelength dependence was found to be different from that of absorption (Fig. 7).

This study was intended to clarify some points on the effects of the lens on visual function. It is tempting to try to use the results also for understanding of properties of the lens. But, because of our intention, the experimental approach was not ideally suited for a study of properties of the lens material. In our approach the central 4 mm diameter part of the lens, from anterior to posterior was used. So, parts of the lens with potentially very different scattering characteristics, contributed. This is presently investigated (van den Berg, Boellaard & Verkruysse, 1994), and it seems that different parts of the lens indeed have different scattering characteristics. So, the observed constancy may partly result from a combination of different effects. This limits the validity of interpreting the present data in terms of the scatterers that may be present in the lens.

Many authors have studied scattering in normal and cataractous lenses, and have developed theories on potential scatterers in the lens material (Benedek, 1971; Jedzidiniak, Kinoshita, Yates, Hocker & Benedek, 1972; Tanaka & Benedek, 1975; Bettelheim & Paunovic, 1979; Bettelheim & Ali, 1985; Delaye & Tardieu, 1983; Tardieu & Delaye, 1988). Bettelheim (1985) points towards important discrepancies between current theories with regard to the size of the *significant* scatterers. The wavelength dependence studied by us is a new entry to this discussion. In general, for small scatterers the wavelength dependence of scattered light should be strong, whereas for scatterers that are not (much) smaller than wavelength, the wavelength dependence should be weak. So, the present results support Bettelheim's conclusion that the significant scatterers are relatively large.

Also *in vivo*, (potential) wavelength dependence of intraocular light scattering has attracted attention (see Vos, 1984). Often reference has been made to Rayleigh scattering. But this is unjustified since Rayleigh scattering has a very strong wavelength dependence (the blue of the sky), never found for intraocular light scattering. Wooten and Geri (1987) carefully studied this question and found no effects of wavelength for an annulus of 3–8 deg. Also Whitaker, Steen and Elliott (1993) found little wavelength effects. van den Berg, IJspeert and de Waard (1991) found intraocular light scattering to be slightly larger (up to a factor of 2) for red light as compared to green light, especially for larger angles up to 25 deg. This was attributed to scattering from the eye wall, not the lens. The present results show the wavelength dependence of lens scattering to be of opposite sign, and to be weak (a factor of 2 at 10 deg). These two opposing wavelength effects might be an explanation for the failure in literature to establish a clear wavelength dependence for intraocular light scattering.

The fact that angular dependence of scattered light was more or less constant, irrespective of its intensity, suggests that in the lens light is scattered only once. It seems that scatterers are present in the normal lens with scattering characteristics described by the power law. The results further suggest that in cataract formation scatterers are added with this same scattering characteristic, irrespective of cataract type. Regrettably our cataract classification was crude. Chylack *et al.* (see e.g. Chylack, Lee, Tung & Cheng, 1983; Chylack, Wolfe, Singer, Leske, Bullimore, Bailey & McCarthy, 1993) have designed standardized classification procedures. But since all cataracts had more or less the same shape of scattering characteristics (values of $p$) this is of little consequence for this conclusion. But the crudeness may have obscured more detailed relations between $p$ and cataract type. Also, it may have caused the relation between the vertical position of the scattering characteristics (values of the regression constants) and the cataract classification to be somewhat erratic (Table 1).

If the number of scatterers is relatively low, light is scattered only once (single scattering). The intensity is proportional to the number of scatterers. This might be an explanation for the observed constancy of shape, more or less independent of scattering intensity. If the number of scatterers is high, light can be scattered twice or more (multiple scattering). When multiple scattering is important, the shape of the scattering characteristic changes. The scattering characteristic becomes more flat, at first around $\Phi = 0$ deg. The somewhat convex shape of the scattering characteristics of lenses 167 and 176 might be a first sign of multiple scattering. Maybe in the study of Bettelheim and Chylack (1985) multiple scattering was even more important, since their characteristic was much more flat. Note that completely diffuse media like opal glass have a completely flat scattering characteristic. To assess whether this interpretation is correct, our present data are too limited. More thorough theoretical study is needed to interpret the data further, but this is beyond the scope of the present study.

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